Example 6a: Local x-y Plots

As illustrated in a number of the previous example problems, access is given to the MAC/GMC 4.0 local field quantities through generation of ASCII files representing data of particular subcells. This example problem exercises this micro scale x-y plot capability to show how certain micro and macro field quantities are related. The simple 2×2 square fiber, square pack RUC architecture is employed to represent a continuous 0.25 fiber volume fraction SiC/Ti-21S composite at 650 °C subjected to applied transverse strain.

MAC/GMC Input File: **example_6a.mac**

```
MAC/GMC 4.0 Example 6a - Micro x-y plots
*CONSTITUENTS
  NMATS=2
  M=1 CMOD=6 MATID=E
  M=2 CMOD=4 MATID=A
*RUC
  MOD=2 ARCHID=1 VF=0.25 F=1 M=2
*MECH
  LOP=2
  NPT=2 TI=0.,200. MAG=0.,0.02 MODE=1
*THERM
  NPT=2 TI=0.,200. TEMP=650.,650.
*SOLVER
  METHOD=1 NPT=2 TI=0.,200. STP=1.
*PRINT
  NPL=6
*XYPLOT
  FREQ=5
  MACRO=2
   NAME=example_6a  X=2 Y=8
   NAME=example_6ai X=2 Y=14
  MICRO=8
   NAME=example_6a_11  IB=1 IG=1 X=2 Y=8
   NAME=example_6a_11i IB=1 IG=1 X=2 Y=14
   NAME=example_6a_12  IB=1 IG=2 X=2 Y=8
   NAME=example_6a_12i IB=1 IG=2 X=2 Y=14
   NAME=example_6a_21  IB=2 IG=1 X=2 Y=8
   NAME=example_6a_21i IB=2 IG=1 X=2 Y=14
   NAME=example_6a_22  IB=2 IG=2 X=2 Y=8
   NAME=example_6a_22i IB=2 IG=2 X=2 Y=14
*END
```

Annotated Input Data

1) Flags: None

2) Constituent materials (***CONSTITUENTS**) [KM_2]:
Number of materials: 2 (`NMATS=2`)

Materials:	SiC fiber	(MATID=E)
	Ti-21S	(MATID=A)
Constitutive models:	SiC fiber: linearly elastic	(CMOD=6)
	Ti-21S matrix: Isotropic GVIPS	(CMOD=4)

3) Analysis type (***RUC**) → Repeating Unit Cell Analysis [KM_3]:

Analysis model:	Doubly periodic GMC	(MOD=2)
RUC architecture:	square fiber, square pack	(ARCHID=1)
Fiber volume fraction:	0.25	(VF=0.25)
Material assignment:	SiC fiber	(F=1)
	Ti-21S matrix	(M=2)

4) Loading:

a) Mechanical (***MECH**) [KM_4]:

Loading option:	2	(LOP=2)
Number of points:	2	(NPT=2)
Time points:	0., 200. sec.	(TI=0.,200.)
Load magnitude:	0., 0.02	(MAG=0.,0.02)
Loading mode:	strain control	(MODE=1)

b) Thermal (***THERM**) [KM_4]:

Number of points:	2	(NPT=2)
Time points:	0., 200. sec.	(TI=0.,200.)
Temperature points:	650., 650. °C	(TEMP=650.,650.)

c) Time integration (***SOLVER**) [KM_4]:

Time integration method:	Forward Euler	(METHOD=1)
Number of points:	2	(NPT=2)
Time points:	0., 200. sec.	(TI=0.,200.)
Time step sizes:	1. sec.	(STP=1.)

5) Damage and Failure: None

6) Output:

a) Output file print level (***PRINT**) [KM_6]:

Print level:	6	(NPL=6)

b) x-y plots (***XYPLOT**) [KM_6]:

```
*XYPLOT
  FREQ=5
  MACRO=2
   NAME=example_6a  X=2 Y=8
   NAME=example_6ai X=2 Y=14
  MICRO=8
   NAME=example_6a_11  IB=1 IG=1 X=2 Y=8
   NAME=example_6a_11i IB=1 IG=1 X=2 Y=14
   NAME=example_6a_12  IB=1 IG=2 X=2 Y=8
   NAME=example_6a_12i IB=1 IG=2 X=2 Y=14
```

```
NAME=example_6a_21  IB=2 IG=1 X=2 Y=8
NAME=example_6a_21i IB=2 IG=1 X=2 Y=14
NAME=example_6a_22  IB=2 IG=2 X=2 Y=8
NAME=example_6a_22i IB=2 IG=2 X=2 Y=14
```

Frequency:	5	(FREQ=5)
Number of macro plots:	2	(MACRO=2)
Macro plot names:	example_6a	(NAME=example_6a)
	example_6ai	(NAME=example_6ai)
Macro plot x-y quantities:	ε_{22}, σ_{22}	(X=2 Y=8)
	ε_{22}, ε^i_{22}	(X=2 Y=14)
Number of micro plots:	8	(MICRO=8)
Micro plot names:	example_6a_11	(NAME=example_6a_11)
	example_6a_11i	(NAME=example_6a_11i)
	example_6a_12	(NAME=example_6a_12)
	example_6a_12i	(NAME=example_6a_12i)
	example_6a_21	(NAME=example_6a_21)
	example_6a_21i	(NAME=example_6a_21i)
	example_6a_22	(NAME=example_6a_22)
	example_6a_22i	(NAME=example_6a_22i)
Micro plot subcell indices:	1, 1	(IB=1 IG=1)
	1, 2	(IB=1 IG=2)
	2, 1	(IB=2 IG=1)
	2, 2	(IB=2 IG=2)
Micro plot x-y quantities:	ε_{22}, σ_{22}	(X=2 Y=8)
	ε_{22}, ε^i_{22}	(X=2 Y=14)

The major difference in the data specification between micro and macro plots is, with micro plots, the subcell for which the data are to be plotted must be specified. In the present doubly periodic GMC example, the $\beta\gamma$ indices are specified. In the case of triply periodic RUC analysis, the three $\alpha\beta\gamma$ indices are specified. Finally, in the case of laminate analysis, the layer from which the subcell is taken must be specified. In addition, there are some micro scale quantities that may be specified for x-y plot file generation that cannot be specified for macro scale x-y plots (e.g., constitutive model state variables, debonding parameters). For more information on micro x-y plots, see the MAC/GMC 4.0 Keywords Manual Section 6.

7) End of file keyword: (***END**)

Results

Figure 6.1 shows the RUC employed in the present example plus the $\beta\gamma$ indices of each subcell and the applied loading. Figure 6.2 is a plot of the local and global σ_{22}-ε_{22} response of the SiC/Ti-21S composite. Examining the four subcell curves, the Subcell 11 curve, which is associated with the fiber, is stiff, elastic, and experiences a large local σ_{22} stress. The subcell that is in series with the fiber along the loading direction (Subcell 12) experiences the same σ_{22} stress as the fiber subcell (at a given point in time), but, since the material associated with the subcell is Ti-21S, the subcell response is more compliant and exhibits inelastic deformation. The remaining two subcells (21 and 22), which are in parallel with the fiber (with respect to the loading direction) experience far less σ_{22} stress than do subcells 11 and 12. While the σ_{22} stress is the same for subcells 21 and 22 (at a given point in time), the ε_{22} strain experienced by the subcell adjacent to the fiber (Subcell 21) is significantly higher.

A final point illustrated by Figure 6.2 involves the volume averaging of the subcell stresses and strains. As shown, if the four subcell σ_{22} stress and ε_{22} strain values are averaged in a volume-weighted sense at each point, the resulting averaged σ_{22}-ε_{22} curve is identical to the macro (composite) σ_{22}-ε_{22} curve plotted directly from the macro MAC/GMC 4.0 x-y plot file. The fact that the volume weighted micro stress and total strain components sum to the macro stress and total strain components is an important attribute of a micromechanics model and is often considered a consistency condition. In fact, the formulation of GMC enforces this consistency condition.

In contrast, Figure 6.3 plots the local subcell inelastic strain ε_{22}^{i} vs. the local total strain ε_{22}. The fiber subcell (11) exhibits no inelastic strain as the fiber material is elastic. The subcells adjacent to the fiber (12 and 21) exhibit a great deal of inelastic strain, while Subcell 22 exhibits less. However, when the volume weighted average of the subcell inelastic strain ε_{22}^{i} values is taken at each point, the resulting curve does not correspond to the macro (composite) level curve plotted directly from the MAC/GMC 4.0 macro x-y plot file. Thus, while a consistency condition is applicable to the total strain components, such a condition does not exist for the inelastic strain components. Similarly, since the total strain is the sum of the elastic, inelastic, and thermal strains, the elastic and thermal strains do not obey a consistency condition either.

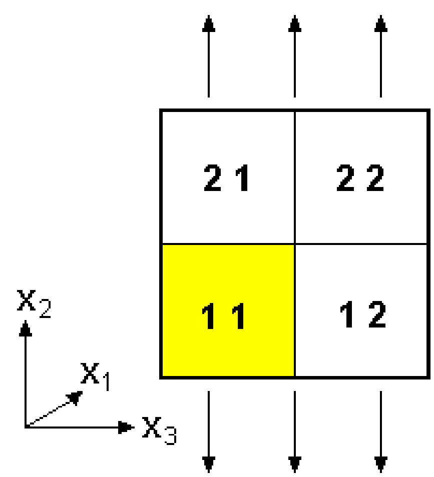

Figure 6.1 MAC/GMC 4.0 2×2 doubly periodic repeating unit cell with subcell indices identified.

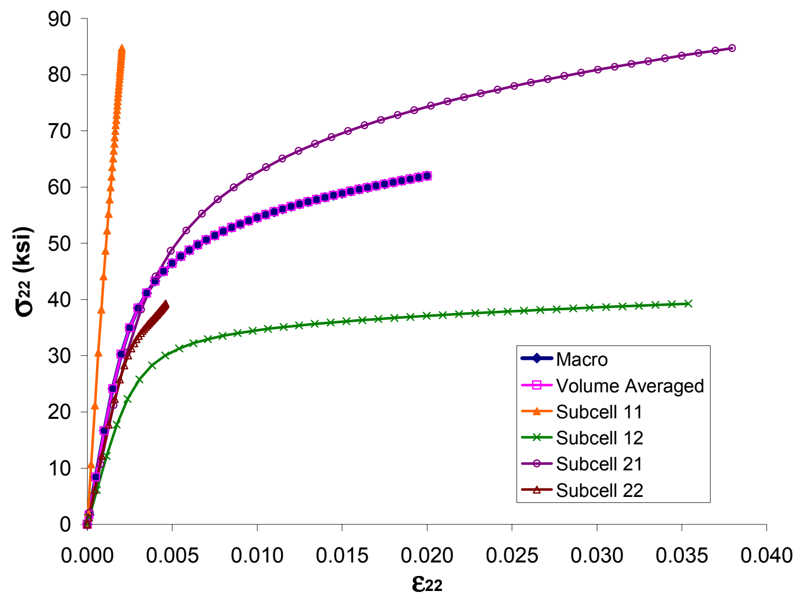

Figure 6.2 Example 6a: Macro (composite) and micro (subcell) stress-strain curves for 25% SiC/Ti-21S at 650 °C.

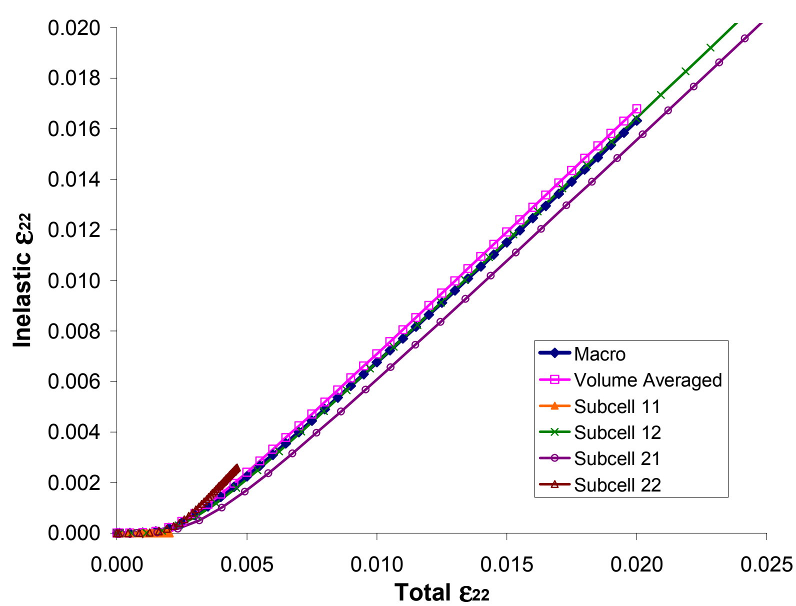

Figure 6.3 Example 6a: Macro (composite) and micro (subcell) inelastic strain vs. total strain plots for 25% SiC/Ti-21S at 650 °C.